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# FINAL REPORT

## Design, Fabrication, Test Qualification and Price Analysis of a Third Generation Solar Cell Module



June, 1982

Prepared for
the
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

Contract Number 955410

by
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ABSTRACT

This final report, of contractual efforts by Photowatt International Incorporated, presents the design, fabrication, test and qualification of a "Third-Generation" intermediate load solar cell module. Included is a technical discussion of the module detailed design, preliminary design review, design modifications, and environmental testing. A standardized pricing system is utilized to establish the cost competitiveness of this module design.

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## 1.0 Introduction

This program initiated in 1979, has undergone several modifications. An initial module design that utilized shaped cells was modified, with JPL program approval. The reconfigured, third-generation design embodied 72 three-inch diameter cells, which were connected in a six parallel by twelve series cell matrix. Figure 1.1 depicts the overall module layout. This design utilizes Czochralski (CZ) silicon cells with redundant across-the-cell copper ribbons. The encapulation system consists of a low-iron tempered glass superstrate and Tedlar*-aluminum foil-Tedlar backside moisture barrier that is thermo-vacuum laminated with polyvinyl butyral (PVB). Edge sealing was accomplished with lead foil tape. The lead tape was overcoated with polyester to increase circuit to case isolation. The laminate was then encased in a gasketed aluminum extrusion frame. The initial aluminum extrusion corner construction, which utilized a barred steel retainer clip, was modified to include stainless steel rivets. Addition of the rivets was necessary to maintain structural integrity during temperature cycling.

A one-piece gasket was selected after intermittant success in attaining the required circuit-to-case isolation. This formed gasket provides a complete and repeatable dielectric at each of the four corners, and thus insures that the designed circuit-case isolation is maintained.

AMP "SOLAR-LOK" terminals were utilized in the final design, for ease of module-to-module field connects, and to facilitate use of external by-pass diodes.

The final Photowatt third-generation, intermediate load module design passed the JPL Block IV qualifications tests with an average power degration of +.5 per cent. The average power output of the qualification modules is 38.15 watts (100 $MW/CM^2$, 28C). This equates to 6.7 watts per square foot of total module area. The following sections provide a detailed description of the module and pertinent results of program design reviews and qualification testing.

## 2.0 Technical Discussion

The third-generation intermediate load module was Photowatt's initial design in which a thermo-vacuum lamination process was utilized and that the solar cell circuit was specifically configured for the needs of an intermediate load array. The initial design also incorporated internal (redundant) by-pass diodes and a labor-saving corner attachment approach.

## 2.1 Detailed Design

The Photowatt third-generation module detailed design started with known potential photovoltaic failure modes and their respective design solutions. Additionally, there was a desire to integrate productibility requirements into the Block IV design.



*Trademark of DuPont

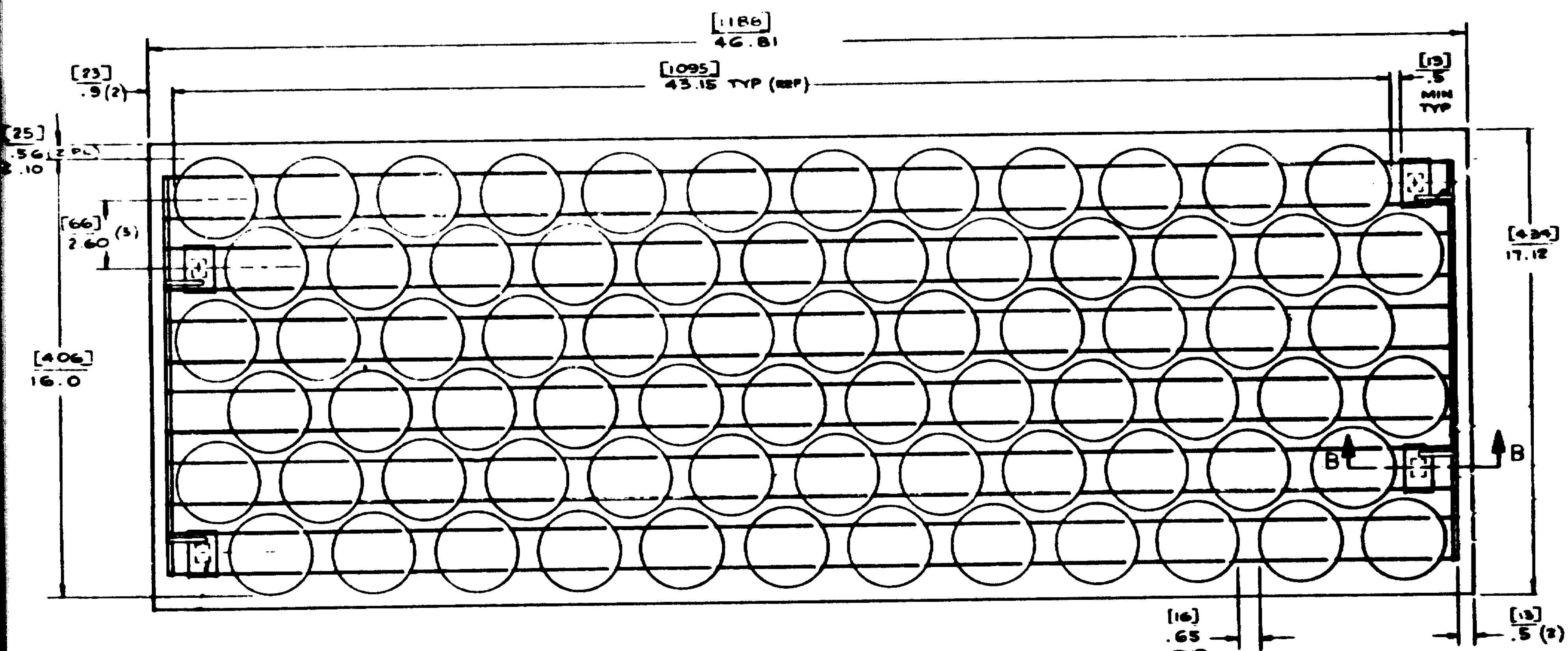



Figure 1.1 Block IV Module Lay-out

Photowatt solar cell processing equipment available at the time of the initial design dictated the three inch diameter CZ cells be utilized. Therefore, the electrical characteristics and packaging efficiency of several alternative circuits were evaluated. It was decided that a six parallel by twelve series cell circuit allowed the best compromise amongst power density, voltage, dimensional and producibility constraints. This circuit configuration, when combined with by-pass diodes, provided a reasonable power building block for most intermediate-load applications.

The cell metal pattern was next assessed. It was desired to minimize three factors, series resistance, shadowing losses and broken cell related module power losses. A compromise cell metal pattern was selected and is shown in Figure 2.1.

This pattern, when combined with redundant across-the-cell copper ribbons, shadowed nine per cent of the cell. It also contributed considerably to the average curve fill factor of .74 for the qualification test modules. The two main bus collectors were spread further apart than optional for series resistance considerations. This, combined with the across-the-cell copper ribbons, lessened the potential power loss should a cell fracture occur in the field. The maximum loss occurs when the cell fractures just outside of a collector bus. This equates to an individual cell loss of 16 per cent. Since there are six paralleled cell strings, the overall module power loss is less than 3 per cent, for a worst case single fracture. The metal system can accommodate most other simple fractures without power loss. This represents a considerable improvement over most previous module designs in which a single cell fracture could result in total loss of power.

Since the cell-to-cell interconnect ribbon is particularly susceptible to thermally induced fatigue, continuous strain relieving, in the form of rippling, was utilized. Preliminary thermal shock ($LN_2$-RT water) testing of several configurations lead to the selection of a ripple amplitude of 10 mils and wavelength of 60 mils. A 3 mil thick by 80 mil wide annealed (Alloy 110) copper ribbon was utilized.

Solid copper buses (20 mils by 200 mils) were employed, at each end of the twelve series cell strings, to parallel connect the six strings. In the initial design, these buses were directed from each end of the module, under a string of cells, to a central location, where two redundant by-pass diodes and the AMP SOLAR-LOK connector housings were installed. Subsequent evaluation of the internally positioned by-pass diodes lead to their placement outside of the module.

The encapsulation system selected for the Photowatt Block IV module is a glass superstrate design. The solar cell electrical subassembly is embedded in polyvinyl butyral (PVB) which is sandwiched between a sheet of low-iron, tempered glass and a backside moisture barrier. The backside moisture barrier is a composite of Tedlar/aluminum foil/Tedlar. This encapsulation system has proved itself in several low-voltage field applications. It does require edge sealing, which is provided by a lead foil tape.

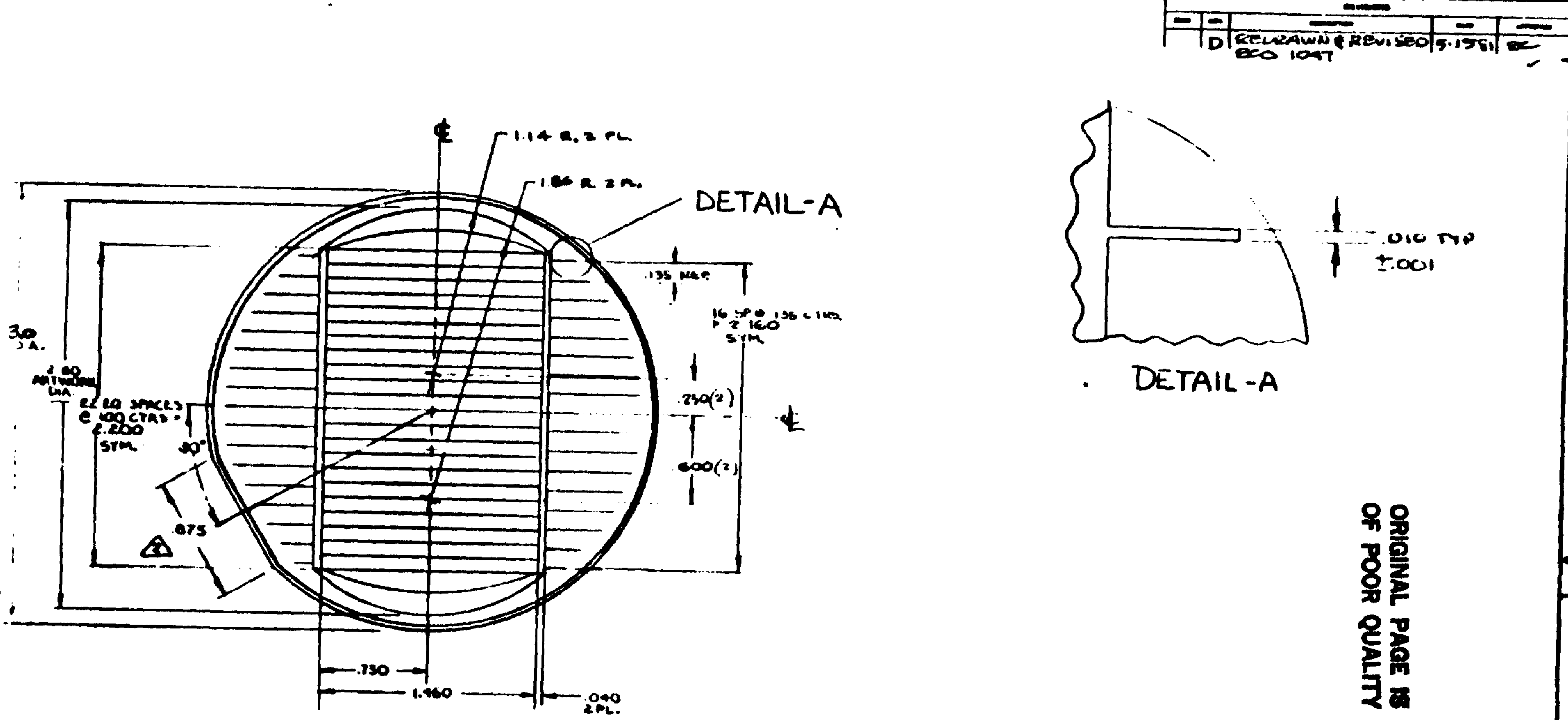



Figure 2.1

5. USE ARTWORK # 10-71-0303-2 FOR FRONT SOLID PRINT (WITH FLATS).
4. USE ARTWORK # 10-71-0249-2 FOR FRONT SOLID PRINT (IF NO FLATS).
3. USE ARTWORK P/N10-10.2436 FOR FRONT ELECTRODE PRINT.
2. FLAT OPTIONAL.
1. TYP CELL THICKNESS .020 ±.005
NOTES:

955410
MICK
PHOTOWATT
SOLAR CELL 3" DIA
JPL BLK IV
C
10-9018
D

The primary area of concern when this encapsulation system is utilized in high voltage applications is a potential electrical path between the circuit and frame, i.e., the backside aluminum foil. The initial design specified two sheets of 15 mil thick PVB between the circuit and backskin. The inner layer of Tedlar (1.5 mils thick) adds to the electrical isolation, as does (3 mil) layer of mylar tape of the perimeter of the laminate. Initial testing of this design showed circuit-frame breakdown in the 5000-6000VDC range. At that time, it was decided to treat the perimeter gasket (between the laminate and frame) as a cushioning member only. This allowed the direct use of the extruded gasket material with a single knife cut, to conform around the laminate corners. This eliminated the cost of a single-piece formed gasket; but created exposed areas at the corners. Measurements of two modules after the complete sequence of qualification testing showed that one module experienced breakdown at 1250VDC and second module at 1500VDC. The breakdown occurred at one corner in each of the two modules. These results initiated a design/manufacturing evaluation which culminated in the selection of a one-piece gasket. The one-piece gasket specification requires that the corner construction be free of pin-holes and that the gasket be loaded in compression throughout the -40C to +90C temperature range.

The frame selected for the Block IV module is an anodized aluminum extrusion of an "E" configuration. Its height is 2.0 inches and its base is 1.0 inches wide. The initial corner attachment design specified the mitering of the extrusions and use of a barbed retension clip. This approach minimized the piece part fabrication and frame assembly labor. A single ($45^{o}$ ) miter cut was needed for each end of the aluminum extrusion and the module could be framed with simple air-actuated cylinder. Environmental testing of this design resulted in gaps occurring at the corners of some modules. Rivets were added at each corner to insure their mechanical integrity. Environmental testing of the riveted corner construction showed that they are an effective solution. Characteristics of the Photowatt Block IV Module are presented in Figure 2.2.

## 2.2 Preliminary Design Review

A preliminary design review of the Block IV design was held at the JPL. The module electrical, mechanical and physical attributes were discussed in detail. Photowatt action items from the review were, 1) provide a clear definition of the cell interconnect strain relief design, 2) assess the potential galvanic interaction between the frame (aluminum) and corner retaining clip (zinc plated steel) and, 3) propose cracked cell criteria. These action items were completed and the pre-production modules fabricated.

## 2.3 Environmental Testing

An initial group of modules were subjected to the Block IV qualification testing sequence. Modules within this group (both the control and test modules) exhibited considerable variation in electrical output. This variation of output power was traced to faulty by-pass diodes.

Figure 2.3 Summary of environmental Qualification Testing

| Module Serial No. | Environmental Test | Power Output (Watts) | Per Cent Change in Power |
|---|---|---|---|
| 2032 | As-received | 38.28 | -- |
| 2032 | Temperature | 38.32 | +.1 |
| 2032 | Humidity | 38.50 | +.5 |
| 2032 | Mechanical (±50PSF) | 38.60 | +.8 |
| 2032 | Twist | 39.25 | +2.5 |
| 2032 | Hail | 38.64 | +.9 |
| 2033 | As-received | 39.62 | -- |
| 2033 | Temperature | 39.14 | -1.2 |
| 2033 | Humidity | 39.39 | -.6 |
| 2033 | Mechanical (±50PSF) | 39.67 | +.1 |
| 2033 | Twist | 40.14 | +1.3 |
| 2033 | Hail | 39.71 | +.2 |
| 2035 | As-received | 36.95 | -- |
| 2035 | Temperature | 36.18 | -2.0 |
| 2035 | Humidity | 36.19 | -2.0 |
| 2035 | Mechanical (±50PSF) | 36.68 | +.7 |
| 2035 | Twist | 37.26 | +.8 |
| 2035 | Hail | 36.93 | +.5 |
| 2036 | As-received | 38.73 | -- |
| 2036 | Temperature | 38.97 | +.6 |
| 2036 | Humidity | 38.53 | -.5 |
| 2036 | Mechanical (±50PSF) | 39.31 | +1.5 |
| 2036 | Twist | 39.69 | +2.5 |
| 2036 | Hail | 39.32 | +1.5 |
| 2037 | As-received | 37.12 | -- |
| 2037 | Temperature | 36.47 | -1.7 |
| 2037 | Humidity | 37.05 | -.2 |
| 2037 | Mechanical (±50PSF) | 38.21 | +2.9 |
| 2037 | Twist | 37.85 | +1.9 |
| 2037 | Hail | 37.15 | +.1 |

Additionally, disadherence of the connector terminal housings occurred on two test modules; and the corner retaining clips yielded on two test modules, forming gaps at those corners.

These modules were reworked in each of the above stated areas and submitted for evaluation, along with the additional modules as required by contract. Five modules from this group were selected for qualification testing. A summary of the qualification test reults is shown in Figure 2.3. The average power output of these modules (as received at JPL) was 38.14 watts and 38.35 watts after the complete qualification test sequence. During mechanical load (±50 PSF) cycling one module developed an intermittant open in one pair of its redundant output terminals. Two other modules exhibited circuit-to-frame voltage breakdown at 1250 VDC and 1500 VDC respectively.

The edge gasket design modification discussed in Section 2.1 was taken as a corrective action to solve the low circuit-frame isolation voltage exhibited by the two modules during the second qualification test sequence.

## 2.4 Final Design

The final design configuration is presented in Appendix A. This design differs from the initial version primarily in three areas: 1) a one-piece formed edge gasket replaces an earlier version with voids at the laminate corners and allowed circuit-to-frame isolation voltage breakdown, 2) internal by-pass diodes have been eliminated, and 3) rivets have replaced the initially designed corner retaining clips. Additionally, two pre-production processes were modified. They are the detailed procedures for removing an injection molding release agent from the AMP connector housing and the elimination of solder from the cell edges to insure that individual cells would not short front-to-back.

## 3.0 Documentation

Primary documentation for the Photowatt Block IV Intermediate Load Module consists of the Engineering and Manufacturing Documentation package and the Inspection System Plan.

The Engineering and Manufacturing Documentation package primarily consists of 1) the interface control drawing that also is utilized as a top assembly drawing, 2) all piece part and material specifications, and 3) the manufacturing process flow chart. This documentation has been prepared and approved by the cognizant technical monitor. A copy of the interface control drawing is provided in Appendix A.

The Inspection System Plan delineates the specific quality control check points, criteria, and inspection methodology. It represents a working document that, in several respects, quantifies the traditional gray areas that have existed between the module manufacturer and procurement personnel.

Figure 2.2 Photowatt Block IV Model Characteristics

| PARAMETER | VALUE |
|---|---|
| Model Number | ML 1961 |
| Power (100MW/CM$^2$, NOCT) | 35 Watts |
| Cell size | 3.0 inch diameter |
| Cell type | Cz, N on P with P+ |
| Series cells | 12 |
| Parallel cells | 6 |
| Length | 1.2 m |
| Width | .45 m |
| Area | .532 m$^2$ |
| Mass | 7.4 Kg |
| Packing factor | .62 |
| NOCT (80 mw/cm$^2$) | 47 C |
| Cell efficiency | 11.6% |
| Module efficiency | 7.2% |

## 4.0 Price Analysis

The standardized pricing procedure developed by the Jet Propulsion Laboratory for silicon cell solar modules (SAMICS/SAMIS) was utilized to obtain pricing estimates of $11.08, $9.94 , and $8.08 per watt at production rates of ten thousand watts, one-hundred thousand watts, and one megawatt per year respectively.

## 5.0 Conclusions and Recommendations

The Photowatt International Block IV module represents an evironmentally sound design with convenient electrical characteristics for the intermediate load sector. It is based on three inch diameter solar cells, which are more costly per watt to produce than are larger diameter cells.

The encapsulation system has been proven in many hundreds of low voltage applications. It would be desirable to identify a replacement for the polyvinyl butyral (PVB) pottant which does not require a backside moisture barrier (e.g., aluminum foil). If such a pottant can be identified, then the potentially serious problem of circuit-to-case shorts can be eliminated. It is expected that pottants of this nature will evolve over the next several years.

## 6.0 New Technology

Photowatt International, Inc. believes that there were no Subject Inventions made under this contract.

# APPENDIX A

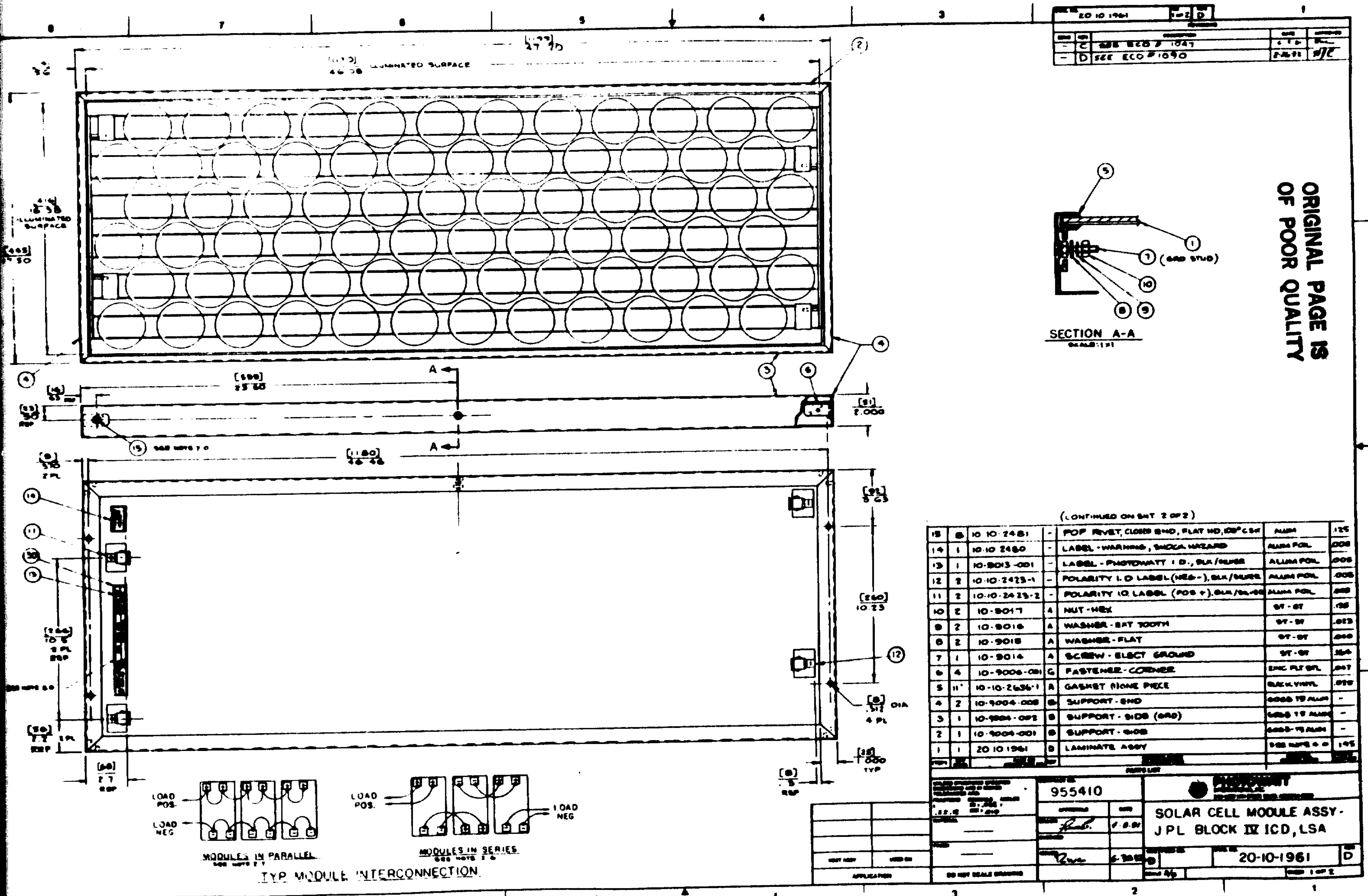
Interface Control Drawing

for

Photowatt International, Inc.

Block IV

Solar Cell Module

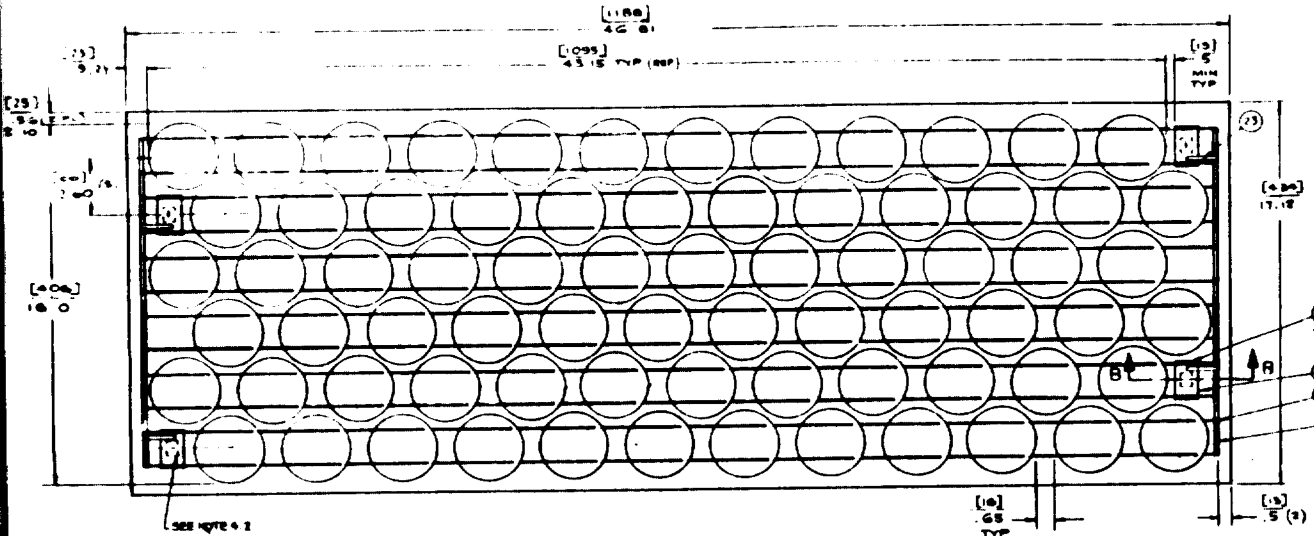



(CONTINUED ON SHT 2 OF 2)

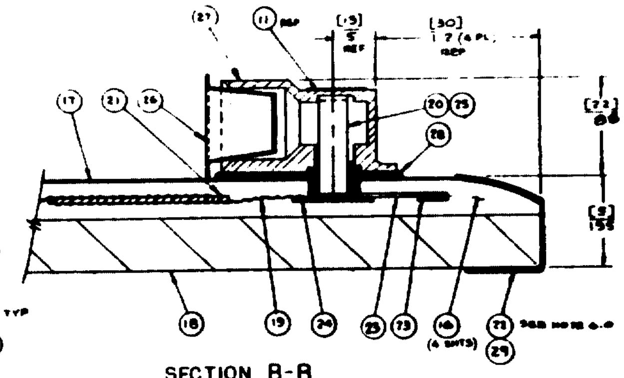
| | | | | | | |
|---|---|---|---|---|---|---|
| 15 | 8 | 10-10-2481 | - | POP RIVET, CLOSED END, FLAT HD, 100° CSK | ALUM | .125 |
| 14 | 1 | 10-10-2480 | - | LABEL - WARNING, SHOCK HAZARD | ALUM FOIL | .008 |
| 13 | 1 | 10-9013-001 | - | LABEL - PHOTOWATT I.D., BLK/SILVER | ALUM FOIL | .008 |
| 12 | 2 | 10-10-2423-1 | - | POLARITY I.D LABEL (NEG -), BLK/SILVER | ALUM FOIL | .005 |
| 11 | 2 | 10-10-2423-2 | - | POLARITY I.D LABEL (POS +), BLK/SILVER | ALUM FOIL | [illegible] |
| 10 | 2 | 10-9017 | A | NUT - HEX | ST - ST | [illegible] |
| 9 | 2 | 10-9016 | A | WASHER - EXT TOOTH | ST - ST | .023 |
| 8 | 2 | 10-9015 | A | WASHER - FLAT | ST - ST | .040 |
| 7 | 1 | 10-9014 | A | SCREW - ELECT GROUND | ST - ST | [illegible] |
| 6 | 4 | 10-9006-001 | G | FASTENER - CORNER | ZINC PLT STL | .047 |
| 5 | 11' | 10-10-2636-1 | A | GASKET (ONE PIECE) | BLACK VINYL | .015 |
| 4 | 2 | 10-9004-003 | B | SUPPORT - END | 6063 T5 ALUM | - |
| 3 | 1 | 10-9004-002 | B | SUPPORT - SIDE (GRD) | 6063 T5 ALUM | - |
| 2 | 1 | 10-9004-001 | B | SUPPORT - SIDE | 6063-T5 ALUM | - |
| 1 | 1 | 20-10-1961 | D | LAMINATE ASSY | SEE NOTE 4.0 | .145 |

PARTS LIST

| | | | | |
|---|---|---|---|---|
| — | C | SEE ECO # 1047 | 6-9-81 | |
| — | D | SEE ECO # 1090 | 2-26-82 | |




REAR VIEW
SEE NOTE 4.1



SECTION B-B
NO SCALE (SEE NOTE 4.2)

8.0 PHOTOWATT I.D. LABEL (13) TO SHOW PART NO 'ML-1961 REV B', SERIAL NUMBER, NOM VOLT, NOM POWER, MAX SYS VOLT, WEEK AND YEAR OF MFG, ADD ITEM (30) OVER LABEL.
7.0 AFTER FRAME COMPONENTS HAVE BEEN ASSEMBLED WITH CORNER FASTENERS, MATCH DRILL THRU CORNERS OF FRAME .129 DIA (8) AND INSTALL RIVET (5) 8PL.
6.0 LEAD FOIL TAPE (22) AND MYLAR TAPE (29) TO BE CONTINUOUS AROUND LAMINATE PERIMETER.
5.0 DUAL DIMENSIONED DWG, DEPICTED THUS [MILLIMETERS / INCH], CONTROLLING DIMENSION: INCH
4.2 AFTER LAMINATION, CUT 3/8 x 3/4 SLOT THRU BACKSKIN BEARING CTR AREA OF ITEM (24) 4 PL, INSTALL ITEMS 26 25 27 28 PER PHOTOWATT PROCESS SPECIFICATION 'P-150' FOR SOLARLOK CONNECTORS.
4.1 REAR VIEW (SHT 2) SHOWN PRIOR TO LAMINATION, ITEMS (17)(20)(21)(26)(27)(28) NOT SHOWN ON THIS VIEW.
4.0 LAMINATE ASSY ITEM (1) MADE FROM ITEMS (16) THRU (19).
3.5 NOMINAL OUTPUT POWER AT SOC. Vmp = 33 WATTS
3.4 NOMINAL OUTPUT VOLTAGE AT NOCT : 5.0 VDC
3.3 MAX MODULE WEIGHT: 16 lbs (7.3 Kg)
3.2 TOTAL ILLUMINATED AREA OF MODULE: 754.8 SQ IN.
3.1 TOTAL AREA OF MODULE: 826 SQ IN
3.0 MODULE DESCRIPTOR: 'ML 1961', 6 PARALLEL STRINGS OF 12 SERIES CELLS.
2.8 MAX RECOMMENDED SYSTEM VOLTAGE: 600 VOLTS.
2.7 UTILIZE PHOTOWATT # 10-9010-005 HARNESS/PLUG ASSY FOR PARALLEL INTERCONNECTION.
2.6 UTILIZE PHOTOWATT # 10-9010-002 HARNESS/PLUG ASSY FOR SERIES INTERCONNECTION.
2.5 ACCEPTABLE GRD STUD INTERFACE MAT'LS: ST-ST, NICKEL, TIN, ZINC.
2.4 ACCEPTED HIGH VOLTAGE SAFETY PRACTICES SHOULD BE USED WHEN MATING CONNECTORS.
2.3 MAX CONNECT/DISCONNECT CYCLES: 1000.
2.2 MAX CONNECTING PLUG INSERTION FORCE: 6 lbs.
2.1 MAX GRD STUD TORQUE: 10 in lbs.
2.0 ELECTRICAL OUTPUT/GRD USER CONSTRAINTS:
1.3 UTILIZE QUARTER INCH OR SAE HARDWARE.
1.2 ACCEPTABLE SUPPORT FRAMEWORK MAT'LS ARE: ALUM, ST-ST, DIELECTRICS.
1.1 MOUNT FLANGES: 6063-T5 ALUM.
1.0 MOUNTING PROVISION MATERIALS:

NOTES: UNLESS OTHERWISE SPECIFIED.

ORIGINAL PAGE IS OF POOR QUALITY

| | | | | | | |
|---|---|---|---|---|---|---|
| 30 | 7.5" | 10-9019-1 | A | TAPE CLEAR - 1" WIDE | 3M/POLYESTER | .002 |
| 29 | 132" | 10-9019-2 | A | TAPE - CLEAR, 3/4" WIDE | 3M/POLYESTER | .002 |
| 28 | A/R | 10-9009 | - | EPOXY - STRUCTURAL (GREY) | 3M 2201 | — |
| 27 | 4 | 10-9010-001 | A | CONNECTOR - SOCKET (BLACK) | NYLON 6/6 | — |
| 26 | 4 | 10-10-2479 | - | DUST CAP - PLUG | PLASTIC | .030 |
| 25 | A/R | SN 63 | - | SOLDER - SOLID CORE 63/37 | TIN/LEAD | |
| 24 | 4 | 10-10-2424 | - | TERMINAL PLATE | COPPER | .010 |
| 23 | 34.5 | 10-9011-005 | D | BUS - RIBBON | COPPER | .010 |
| 22 | 11' | 10-9005 | C | TAPE - SEALANT | LEAD | .005 |
| 21 | 72 | 10-9018 | D | SOLAR CELL - 3" DIA JPL | SILICON | .020 |
| 20 | 4 | 10-10-2428 | C | TERMINAL TONGUE | COPPER | .032 |
| 19 | 68' | 10-9011-007 | D | BUS - RIBBON (CELL TO CELL, APPLIED) | COPPER | .003 |
| 18 | 1 | 10-9001-001 | B | GLASS, COVER - TEMPERED | | .125 |
| 17 | | 10-9003-001 | C | BACKSKIN - LAMINATED (SUN YELLOW) | | |
| 16 | | 10-9002-001 | - | FILM, POTTANT (TRANSPARENT SHEET) | PVB | .015 |

955410

SOLAR CELL MODULE ASSY - JPL BLOCK IV ICD, LSA

20-10-1961 D